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Remaining Life Assessment of Offshore Wind Turbines Subject to Curtailment

Anand Natarajan[1,2], *Troels F. Pedersen*[1]

[1] Technical University of Denmark, Department of Wind Energy,
Roskilde, Denmark

ABSTRACT

The fatigue damage reduction versus energy production loss trade-off analysis is demonstrated on a Vestas V-52 turbine by de-rating the turbine power over a specific period corresponding to high measured turbulence using a spinner mounted anemometer. Based on the measured blade root and tower base loads, the benefit of curtailment under high turbulence on lowering the fatigue damage is quantified. A cut-off mean turbulence intensity level of 16% at 15m/s or class-A conditions is chosen as the turbulence level to impact tower base fatigue damage reduction. The turbulence is measured using a spinner anemometer mounted on the V-52. It is shown that the tower base fore-aft damage equivalent moments can at some mean wind speeds be reduced by as much as 30%. The reduction in the blade root damage equivalent moment is not significant for power set point based curtailment. The learnings from this power curtailment strategy based on measured turbulence are extended to an offshore wind farm study case to demonstrate its benefit to life extension or CAPEX reduction of offshore sub structures.

KEY WORDS: Power curtailment, fatigue life, turbulence, loads, wake effects

INTRODUCTION

As wind farms approach their normal design life of 20-25 years, wind farm owners require informed decisions on the remaining life of the wind turbines on the farm and whether life extension beyond the planned design life is feasible. A factor to be considered in the process of remaining life computations is power curtailment of turbines or reduced power production. Most wind turbines in an offshore wind farm are subject to curtailment during some part of their operational life. While curtailment is commonly due to lack of energy demand from the electrical grid, curtailment also results in reduced fatigue on the wind turbine components and reduced wake turbulence behind the curtailed turbine. Since fatigue of key structural components is correlated to wind turbulence, it is beneficial to the turbine life, if the curtailment that is made, is at locations within the farm with high wake turbulence.

Conventional wind turbine instrumentation for wind speed measurements is done using a Nacelle mounted anemometer and wind vane, which when calibrated can measure the 10-minute free stream mean wind speed and wind direction. Modern wind turbines may also be equipped with a nacelle mounted Lidar (Schlipf Mann and Cheng 2013) or a Spinner Anemometer (Pedersen, Demurtas and Zahle, 2015), which can measure the 10-minute mean wind speed, direction and the turbulence (std. deviation of the 10-mean wind speed) fully correlated to the free-stream turbulence. The Spinner anemometer has the added benefit that it is measuring turbulence at a point whereas the Lidar measurement is over a finite volume, which still is useful to quantify the turbulence in the inflow (Dimitrov and Natarajan, 2017).

The wind turbine structure is designed to meet the mechanical loading corresponding to a given wind turbulence class. The fatigue lifetime of the blade, tower etc. is ensured based on the 90% quantile of turbulence for a selected turbulence class. While the turbulence for the rotor-nacelle-assembly (RNA) is typically designed based on the IEC specification (IEC 61400-1, 2005), the tower is designed to site-specific wind conditions. The uncertainties in the wind conditions can be relatively large, especially due to seasonal variations, storms and also changing terrain conditions over the life of the turbine. Thus measurement of turbulence on a continual basis, such as by the use of a spinner anemometer can be a valuable means for verifying that the turbulence is always below the design level or initiating control action for elevated turbulence levels. Based on the exceedance of the measured turbulence over a 10-minute interval, the turbine control system can be configured to react in different ways to lower the load level of the turbine. Such a measurement can be very useful to life extension of wind turbine structures in a wind farm at locations with high wake turbulence. A means of supervisory control is curtailment of wind turbines (Burke and O'Malley, 2011) in a wind farm, which is due to reduced power requirements from the grid. However, curtailment can be made by selecting wind turbine locations that have high wake turbulence within the wind farm.

For the objective of lowering the fatigue damage to the structural components, it is possible to de-rate the turbine by changing the rotor speed set point or the power set point or altering the tip speed ratio curve for variable speed turbines with collective pitch control as the sole load reducing mechanism. The efficacy of reducing the fatigue damage to the blades and tower base based on de-rating the turbine is demonstrated using both simulations on an aeroelastic model of the Vestas V-52 turbine and measurements from the corresponding wind turbine situated on the DTU Risø campus.

Simulated Curtailment Studies

The Vestas V-52 is a variable speed, collective pitch control turbine with a rated power of 850 kW that is achieved at 14m/s. An aeroelastic model of the V52 is used in the HAWC2 software (Larsen and Hansen, 2015) to perform fully coupled load simulations under power curtailment. Load case DLC 1.2 [5], that is, normal operation under normal turbulence is run under IEC class 1A conditions, which has a mean turbulence intensity of 0.16 at 15m/s. This is the highest turbulence class for turbine certification and leads to high amplitude loading on turbine structures.

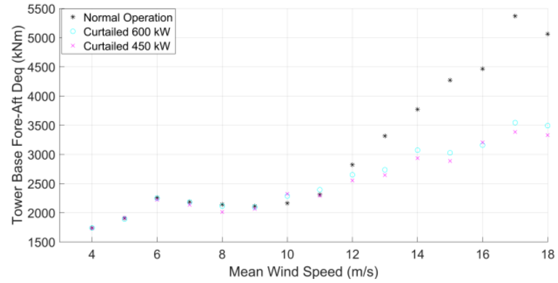
The load simulations are performed under full power conditions, curtailment at 600 kW and at 450 kW to understand the reduction in damage equivalent loads. The curtailment is made only using lower power set points. The variable speed region of the V52 is at mean wind speeds significantly lower than the rated wind speed of 14m/s. This implies that under curtailment of 600 kW, the turbine is still in the fixed speed region and the lower power is only a result of lower generator torque.

Figure 1 shows the reduction in damage equivalent loads obtained at the tower base and blade root from the normal turbulence load simulations. It can be seen that there can be 30% or more reduction in the 10-minute damage equivalent moments in the fore-aft direction at the tower base resulting from curtailment. However, the blade root flap moments show limited damage equivalent load reduction, while the damage equivalent moments in the edge direction are reduced by about 5-10%. Thus, while there may be significant savings on the tower fatigue damage, curtailment does not show significant benefits in reduction of blade root fatigue. This however does not account for possible reduction of fatigue on downstream turbines in a wind farm from reduced thrust loading.

The observations that have been made in Fig. 1 needs to be validated with measurements on an installed turbine. This is proposed to be done using an instrumented Vestas V52 with strain gauges mounted on the blade root and tower base. The mean wind speed and turbulence are measured using a spinner anemometer mounted at the spinner of the wind turbine. The turbine was de-rated from its rated power of 850 kW to 600 kW for a measurement period spanning 1.5 months from Nov. 1 2016 to Dec. 15 2016. The remaining period beyond Dec 15, 2016 pertains to normal operation of the wind turbine. During both periods of operation, several high frequency measurements are continuous logged from the turbine. These comprise of the blade root flap and edge moments, the tower top bending moments, yaw moment, the tower base fore-aft and side-side moment, as well as typical SCADA records such as the rotor speed, power, generator torque and blade pitch angle.

Spinner Anemometer

The measurement of wind speed, turbulence and loads were investigated on the Vestas V52. The calibration of the spinner anemometer was primarily made with data measured during operation with traceability to a met mast cup anemometer at hub height. An internal calibration was made after installation of sonic sensors on the spinner. An inflow angle calibration was made by yawing the rotor in and out of the wind several times.



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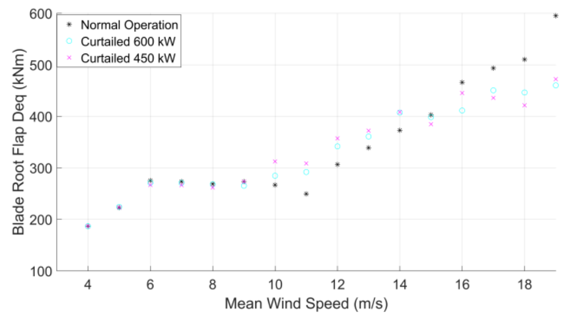

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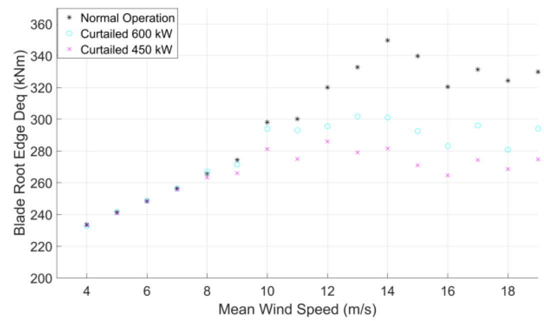

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Figure 1: a) Reduction in 10-min tower base fore-aft damage equivalent moments, b) Reduction in 10-min blade root flap damage equivalent moments, c) Reduction in 10-min blade root edge damage equivalent moments as a function of the mean wind speed determined from aeroelastic simulations

The cup versus spinner anemometer wind speeds measured during operation in the free sector are shown in Figure 2, where a correction factor F1=1.445 is applied on the calibrated K1 velocity conversion value of the spinner anemometer. The equations for these constants can be found in the reference (Pedersen, Demurtas and Zahle, 2015). The F1 constant was quantified from simultaneous measurements from the spinner anemometer against cup anemometer measurements at hub height on a nearby mast during operation of the wind turbine. This factor was derived for high wind speeds where the rotor induction is very low. For lower wind speeds, a correction for the rotor induction was applied to the spinner anemometer measurements. The measured induction (the deviations from the straight line) is shown in Figure 3 as a function of the spinner anemometer measured wind speed (U_{sa}). The induction was binned and an induction function was fitted (Pedersen, Demurtas, Sommer, Højstrup, 2014), as given by:

$$a = B\left(\frac{U_{sa}-C}{A}\right)^{D-1} \cdot \exp\left(-\left(\frac{U_{sa}-C}{A}\right)^{D}\right) \qquad -(1)$$

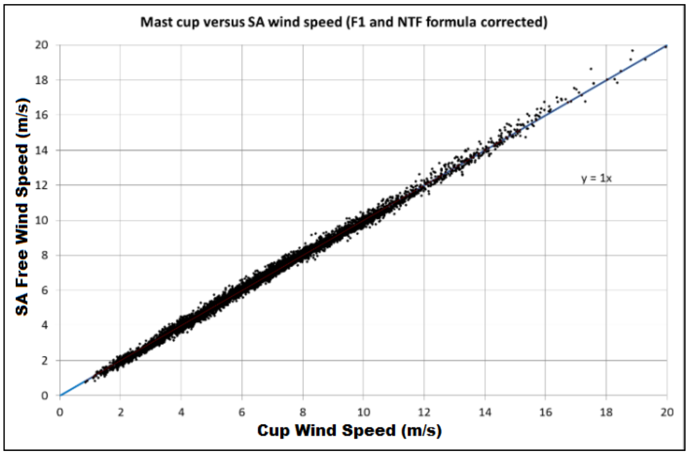


Figure 2 Spinner anemometer wind speed corrected with F1=1.455 and corrected with induction function versus cup wind speed at 44m height

For the V52 turbine, the constants to determine induction were found to: A=5.71, B=0.449, C=3 and D=2. The measured turbulence from the spinner anemometer matches well with the corresponding readings from the cup anemometer as shown in Figure 4.

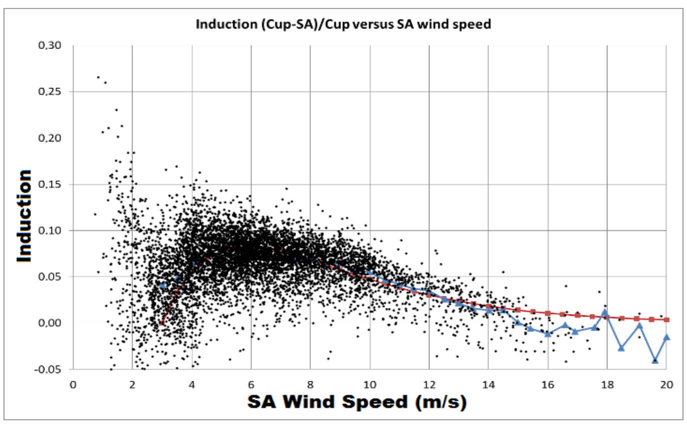


Figure 3: Induction at the spinner anemometer. Red curve is fitted formula. Blue curve is determined with method of bins

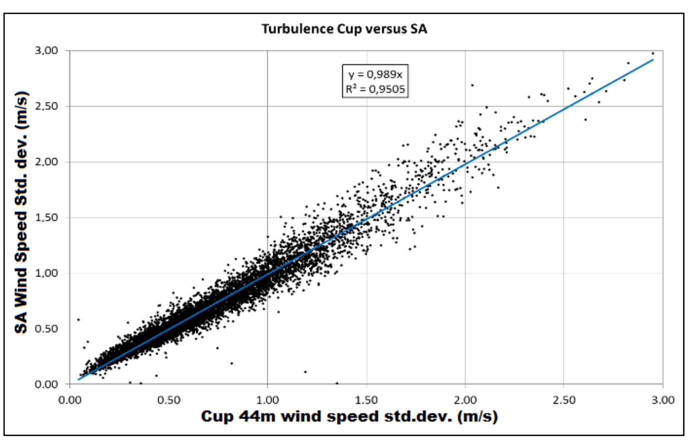
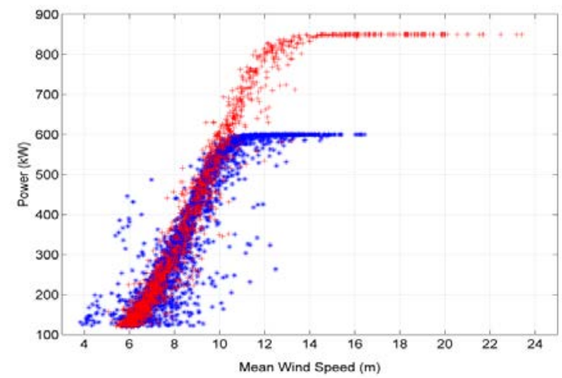


Figure 4: Turbulence (standard deviation) from the spinner anemometer versus cup anemometer at 44m height

The turbulence intensity measured by the spinner anemometer (standard deviation divided by average wind speed) is also nearly the same as the mast measurement (regression line 1.0368). The turbulence intensity relating to the free wind speed also matched well with the mast measurements (regression line 0.9805). The turbulence intensity measured by the spinner anemometer might be dependent on the size of turbine and turbulence structure at the site.

Measured Fatigue Reduction

The wind turbine is de-rated to a max power of 600 kW for a period of 1.5 months and the de-rated power production is compared with the normal power production in Fig. 5a. The turbulence intensity measured during this observation period is shown in Fig. 5b. A threshold of turbulence intensity level of 16% above a mean wind speed of 10m/s is taken as a limiting level of turbulence for evaluating fatigue reduction potential under curtailment. At 15m/s, this corresponds to the mean turbulence intensity for a Class A turbulence class design as used in the aeroelastic simulations described earlier. Figure 6a compares the measured 10-minute normalized damage equivalent moments of the tower base fore-aft moment between the de-rated (curtailed) and



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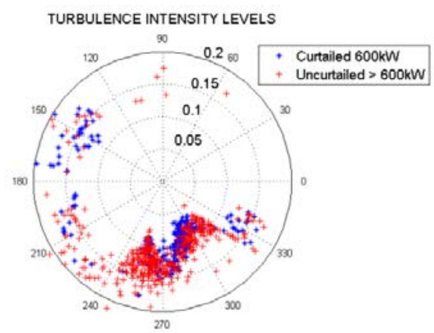

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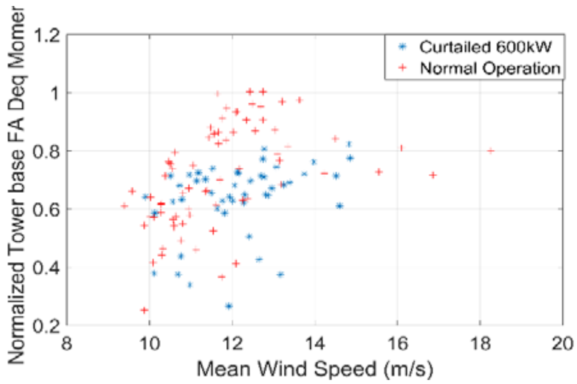
Figure 5: Curtailment of the V52 wind turbine and measured wind turbulence using the spinner anemometer

normal operations. It is seen that the tower base fore-aft damage equivalent moments can at certain mean wind speeds be reduced by as much as 30%; which is of the same order predicted in the aeroelastic simulations in Fig 1a. The maximum possible reduction in the blade root flap damage equivalent moment is shown in Fig. 6b to be negligible, while 5-10% reduction in blade root edge damage equivalent moments is seen. The reasons for the low reduction in the damage equivalent flap moments at the blade root is based on the fact that the curtailed power is still realized at the rated rotor speed of the turbine (reached at 9 m/s) and further reduction in blade root fatigue is possible only if the rotor speed is also significantly reduced. Thus, for the turbine that is being de-rated or curtailed, based on power set-point reduction, a significant potential exists for tower base fatigue reduction, but may not be for blade root fatigue reduction. Also the degree of tower base fatigue reduction is dependent on the wind turbulence level and class A type conditions is recommended as a threshold to realize sufficient benefits.



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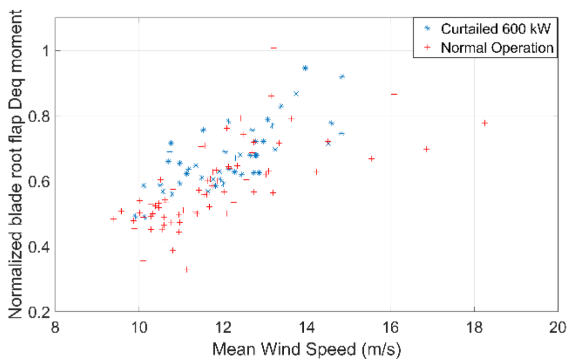

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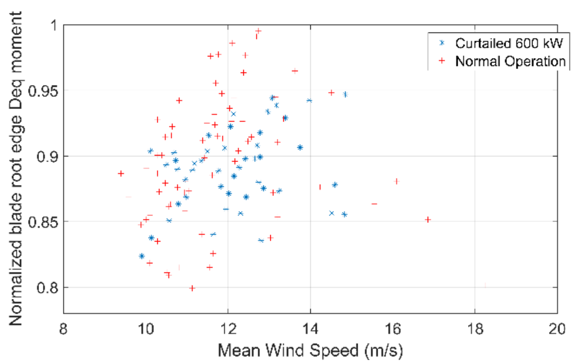

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Figure 6: Measured 10-minute Damage Equivalent Moments at Tower Base and Blade Root of Vestas V52 during normal operation and curtailment.

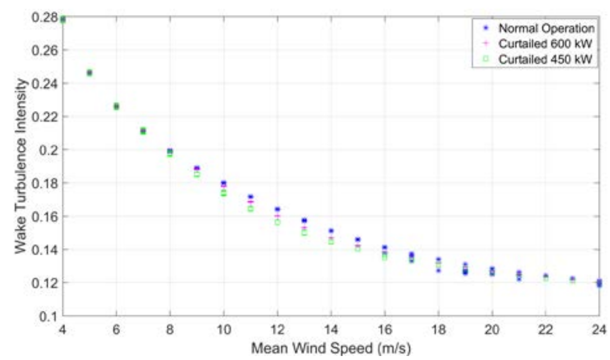
The tower base fatigue reduction can prove extremely useful for offshore wind turbines; since offshore substructures such as jackets and monopiles are fatigue limit driven in their design and the life of these substructures need to be evaluated for life extension or repowering of offshore wind turbines.

Application to lifetime extension of offshore wind turbines

As different offshore wind farms in Europe near 20 years of operation, it is critical that the remaining fatigue life of the constituent wind turbine structures is evaluated (Ziegler and Muskulus, 2016). The fatigue life of blades, tower, and substructure are essentially governed by turbulence under wake situations, even though the wave loading can also influence the fatigue of substructures. Thus overall the wind turbines at the center of the farm are often the most heavily loaded (Dimitrov et.al., 2016) since they are always under wake flow regardless of the prevailing direction of the free stream wind.

While the V52 is a land based turbine, its power and thrust curve characteristics are similar to the Vestas V80 and V90, which are offshore wind turbines. Thus, similar benefits for up-scaled offshore wind turbines with V52 type non-dimensional characteristics are expected. Curtailment of offshore wind farms is often the case during periods of low electricity demand. The lowered thrust from curtailment results in lowered wake turbulence (IEC 61400-1). The benefit of the lowered thrust from curtailment affects both the curtailed turbine and the turbines behind the curtailed turbine through lowered wake turbulence.

The simulated curtailment of the V52 wind turbine from 850 kW to 600 kW in Fig. 1 also resulted in a reduction in aerodynamic thrust by 5% near rated rotor speed. Further curtailment to 450 kW reduces the peak thrust by 12% in comparison to the normal operation. Since reduction in thrust levels influences the turbulence in the downstream wake, the effect of curtailment on the wake turbulence should be quantified.



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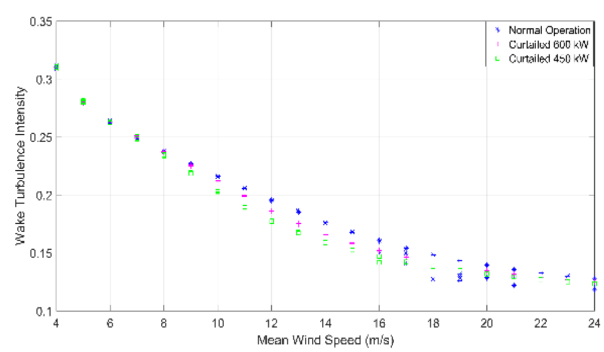

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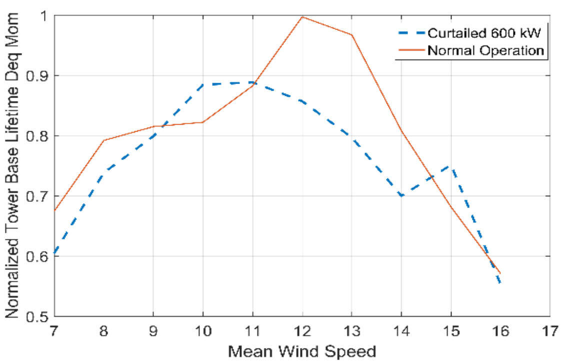
Figure 7: Sten Frandsen added wake turbulence intensity during normal operation and under curtailment for a)7D turbine spacing and b)4D turbine spacing.

Using the Sten Frandsen wake turbulence relation (IEC 61400-1), the wake turbulence in the interior of a wind farm which is more than 2 rows of wind turbines from the free stream is simulated. This standard relationship used in wind turbine design assumes that annually the wakes of 8 neighboring wind turbines next to the affected turbine are to be considered with a directionally probability of 0.06 for each of the 8 wakes. Figure 7a depicts the Sten Frandsen wake turbulence in the center of a wind farm, that is more than 2 rows from the free stream but with 7-rotor diameter spacing (7D) between turbines. Figure 7b depicts the same wake effective turbulence, but now with 4D inter-turbine spacing.

As clearly seen in Fig. 7, there is limited reduction in turbulence intensity at 7D spacing from power curtailment, since the Sten Frandsen turbulence model rapidly reduces the added wake turbulence at greater turbine spacing; becoming equal to the free stream turbulence after 10D. At 4D, about 15% reduction in turbulence intensity is achieved due to curtailment between 11m/s and 16m/s mean wind speeds. In reality, the added wake turbulence may persist longer than 10D based on atmospheric stability and entrainment of the free stream into the wake. However, the benefits from power curtailment may not be seen beyond a distance of 4-5D behind the curtailed turbine based on its impact on the turbulence intensity as seen in Fig. 7.

However, on the curtailed turbine in itself, as seen from Fig.6, there is a reduction in the tower base damage equivalent moment with 30% power curtailment. Figure 8 depicts the variation in the lifetime tower base damage equivalent moment over mean wind speed and the corresponding annual energy capture. The significant reduction in fatigue moments at the tower base for the V52 is seen mainly at mean wind speeds between 11m/s-14m/s in Fig. 8. While the duration of curtailment needs to be decided, up to 5.5 % improvement in the fatigue lifetime at the tower base is feasible with a 30% power curtailment, if the turbulence is at least class A. This may be translated to either material savings in the design of the tower and offshore substructure or increased operational life of the turbine. Thus, the power curtailment needs to be made only at these mean wind speed bins and tailored to the duration of high turbulence. Assuming an SN



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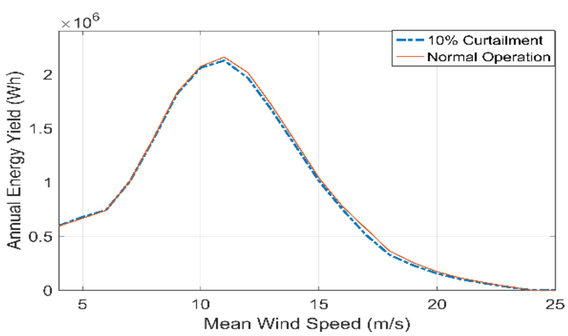

b)

Figure 8: Reduction in Lifetime damage equivalent moments at the tower base and loss in AEP under curtailment 10% of the time

curve slope of 4 for the substructure/tower material, a 5.5% reduction in the damage equivalent load would imply a 24% increase in operating lifetime of the support structure. Assuming the wind turbine is fully available during the life extension period with the same annual Weibull probability of mean wind speed, a 24% extension of lifetime would allow an increase in energy capture of at least 4.2% compared to normal operation without life extension. If the curtailment is limited to only the mean wind speeds between 11m/s-14m/s and if the curtailment occurs at most 50% of the time at these mean wind speeds, it would result in about 10% curtailment of the overall operational time. The loss in lifetime energy production due to curtailment at these mean wind speeds is computed to be less than 2% and therefore this loss is more than compensated via the extended lifetime of the wind turbine.

If in case life extension of the wind turbine is not feasible due to damage of other components in the turbines, then significant CAPEX savings of the substructure during the design phase, resulting from fatigue damage reduction can be accrued. The offshore substructure is the most expensive component of each turbine installation and any savings in the substructure cost is valuable. It is also a fatigue design based structure. Assuming that the stress in the substructure is bending dominated; it implies that the mass of the substructure scales by a factor of (2/3) of the stress change. A 5.5% reduction in bending fatigue stress would thereby imply a 3.5% reduction in the mass of the substructure for meeting the same lifetime target.

CONCLUSIONS

Power set point based curtailment was explored by down rating a Vestas V52 wind turbine and measuring the reduction in loads at the blade root and tower base during the curtailment. It was determined that a 30% power reduction was sufficient to produce a corresponding reduction in tower base damage equivalent moments by 20%-30%, provided the turbulence was at least class A or higher. This requires measurement of turbulence, which was demonstrated using a spinner anemometer mounted to the V52. The blade root edge fatigue damage may be reduced by 5%, but power set-point based curtailment does not reduce blade root flap fatigue significantly.

The measured fatigue reduction under curtailment was seen to apply on a limited mean wind speed bin of 11m/s-14m/s assuming V52 type characteristics, whereby the reduction in lifetime fatigue damage equivalent bending moment at the tower base was 5.5%. This implies a 24% increase in the lifetime of the turbine, which increases the overall energy produced by the farm in its lifetime significantly more than the loss due to curtailment. If lifetime extension is not feasible for other reasons, the reduction in tower base fatigue can also contribute to a 3.5% reduction in the support structure CAPEX during its design phase.

As applied to wind farms under wake conditions, there is greater benefit to load reduction at the tower base on the curtailed turbine rather than downstream turbines, if the inter-turbine distance in the farm was greater than 4-rotor diameter. The potential savings in tower base fatigue is of high value offshore due to the significant cost of the offshore substructure, which cost may be reduced by lowered fatigue or offset by increased farm lifetime.

ACKNOWLEDGEMENTS

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REFERENCES

Burke, D. J. and O'Malley, M. (2011). "Factors influencing wind energy curtailment", *IEEE Transactions on Sustainable Energy*, 2 (2), 185-193

Dimitrov N.K. and Natarajan A. (2017). "Application of simulated lidar scanning patterns to constrained Gaussian turbulence fields". *Wind Energy Journal*, 20(1):79–9

Galinos, C., Dimitrov, N., Larsen, T.J., Natarajan, A. and Hansen, K.S. (2016). "Mapping wind farm loads and power production - a case study on Horns Rev 1", *Journal of Physics: Conference Series (online)*, 753(3), 032010.

IEC 61400-1 (2005). "International Electro technical Committee, IEC 61400-1: Wind Turbines Part 1: Design Requirements." Edition 3, Geneva.

Larsen, T.J, Hansen, A.M. (2015). "How 2 HAWC2, the user's manual". Dept. of Wind Energy Report no. DTU Risoe-R-1597. Technical University of Denmark http://www.hawc2.dk/-/media/Sites/hawc2/HAWC2%20Download/HAWC2%20manual/manual_version_4-6.ashx

Pedersen, T. F., Demurtas, G., and Zahle, F. (2015). Calibration of a spinner anemometer for yaw misalignment measurements. *Wind Energy Journal,* 18: 1933–1952

Pedersen T.F., Demurtas G., Sommer A. and Højstrup J. (2014). "Measurement of rotor centre flow direction and turbulence in wind farm environment", *Journal of Physics: Conference Series (Online),* Vol. 524, No.1, 012167.

Schlipf, D., Mann, J. and Cheng, P.W. (2013). "Model of the correlation between lidar systems and wind turbines for lidar assisted control," *Journal of Atmospheric and Oceanic Technology*, vol. 30, no. 10, pp. 2233–2240.

Ziegler, L. and Muskulus, M. (2016)." Fatigue reassessment for lifetime extension of offshore wind monopile substructures", *Journal of Physics: Conference Series (online),* Volume 753, 092010.